10 Management guide for planting and production of switchgrass as a biomass crop in Europe[12]

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Introduction

Switchgrass (*Panicum virgatum* L.) is a warm season perennial herbaceous grass that is established from seed. It develops rhizomes and is also deep rooting, often more than 2 m. It grows 50-250cm tall depending on the variety and climatic conditions. It has the C4 photosynthetic pathway and is an efficient user of nitrogen and water. This makes it potentially a very productive grass. Productivity will vary between 6 tonnes dry matter (DM)at low fertile Northern European sites up to 25 tonnes at fertile Southern European sites. If properly managed it has long-term productivity potential (>15 years) with a high level of sustainability.

Switchgrass is indigenous to North America and is found from Mexico into Canada but it does not occur naturally above the 55 0 N latitude. There are two main types: lowland types that are found on wetter sites such as flood plains. They have tall, thick, coarse stems and bunch growth habit. The upland type is adapted to drier habitats. It has thinner stems than the lowland type and stem number is greater. Some have a turf -like growth habit.

Switchgrass is best compared to *Miscanthus*, another C4 biomass grass. Compared to *Miscanthus* (gigantheus), switchgrass is smaller, thinner and generally leafier. As it is established from seed, establishment is less expensive and involves less risk than *Miscanthus*, which is propagated by rhizomes, which is more expensive. There are indications that switchgrass is more drought tolerant and may do better under low fertility (low input) conditions

Applications

In the USA switchgrass is used for erosion control and to provide forage under hot and dry conditions. In recent years switchgrass has been intensively studied in North America and more recently in Europe as a potential biomass crop for power production through direct combustion and possibly for lignocellulosic ethanol production. Other uses of switchgrass include fibre production, and wildlife habitat improvement.

Growth cycle

Shoots emerge in spring when soil temperature rise above 10 C. Growth can be very rapid with up to 75% of biomass being formed by mid-summer when flowering occurs. After flowering is complete, stems become lignified and start to senesce, as the plant becomes dormant. In southern European countries the growth cycle may be complete by late summer. During senescence minerals are relocated from leaves and stems to roots and rhizomes where it is stored for the next growth cycle. This natural process improves the quality of the biomass for combustion.

Site selection

Deep soil that has good water holding capacity and adequate drainage is best but switchgrass is adapted to a wide range of soils. Shallow soils, stony soils and occasionally waterlogged soils are also suitable. When grown under low soil fertility and pH (acidity) it will have relatively high yields compared to temperate grass species or energy tree crops like willow coppice

[12] These guidelines are based on available literature and three-year Europe wide small plot experiments. Therefore the guidelines should be seen as preliminary. Improved guidelines should become available as large-scale experiments are conducted in Europe. See www.switchgrass.nl

Previous crop

Spring and summer germinating weeds, especially perennial weeds and volunteers can be a serious threat to switchgrass establishment. Sites with severe weed problems should be avoided but if this is not possible weeds should be treated well in advance of planting. To reduce the risk from weeds it is important to plan ahead. Start your weed elimination strategy in the year before planting. Control of perennial weeds will be better because any re-growth can be dealt with before the switchgrass is sown. Take into account any specific requirements resulting from the previous crop for example, avoid leaving surface residues because it can interfere with sowing and prevent good seed to soil contact.

Site conditions

Switchgrass is slow to establish and it is important to follow basic guidelines that have proved successful in North America and Europe. Eliminate perennial weeds in particular since these are the most difficult to control after the crop has been planted (see previous crop). Prior to cultivation, compacted areas should be sub-soiled. After ploughing, use any secondary cultivation necessary to produce a firm fine seedbed. It has been shown both in the USA and recently in Europe that no-till drilling is also possible.

Soil fertility

Switchgrass is well adapted to low fertility and acid soil conditions. It has a large and deep root system that is very efficient in scavenging nutrients. It utilises mycorrhizae in taking up phosphorus.

Under ideal conditions one should aim for a neutral pH status at planting. In the first year no nitrogen should be applied because it is not necessary for the development of the crop and can promote weed growth leading to competition with seedlings and possibly smothering them. Phosphorus and potassium should be applied if soil availability is low. In later years application of nutrients should be at a level that anticipates rising productivity and also takes into account losses of minerals in harvested biomass. Normally stems are harvested when they are dead, the mineral content is low, and fertiliser application to compensate for this loss may only be required every few years. Nitrogen requirement is low and some studies show that soil reserves, N re-mobilised from roots and atmospheric deposition may be adequate in NW European conditions. On soils of low fertility or where irrigation is applied additional N may be required. The first European studies show that between 0 to 50 kg N/ha/year is adequate for NW European sites while at higher productive sites in southern Europe 50 to 100 kg N/ha/year should be adequate. More specific recommendations for quantity of nutrients cannot be made because it will depend on the fertility status of the site, however phosphorus and potassium levels can be kept low. High N applications may contribute to lodging. Lodging has been observed at several experimental sites in NW Europe and can reduce yield and increase moisture content of the biomass.

Variety choice

A number of varieties are available from North America that have been found to be adapted to European conditions. Variety choice will be governed by the latitude of the site on which planting is intended. Varieties originating from Southern American areas will do best in Southern locations in Europe however they still are productive in Northern Europe but over-winter survival may not be as good as varieties of northern origin. Results from the European switchgrass network show that varieties can be grown further north in Europe than on the American continent probably because maritime influences moderate the climatic conditions.

A wide range of varieties has been tested under European conditions and many have proven to be well adapted. The following varieties have both given good results at their area of adaptation in Europe and are commercially available (in the USA):

Variety Cave-in-Rock is adapted to NW European areas (UK, NL, D).

Variety Kanlow is adapted to more southern areas (Southern UK and D, Northern IT). The variety can experience winter survival problems at more northern latitudes especially in the first year.

Variety Alamo is best suited to Southern regions of Europe (GR, IT). It may not survive winter in Northern Europe, especially in the first year, and quality will be low.

Planting

Seed can be sown in a conventional manner with a drill or direct-drilled (no-till) or broadcast. Whatever method is used, rolling before and after sowing is often desirable, particularly when seed is broadcast to ensure good seed to soil contact but don't roll if the soil is wet because surface compaction or crusting might result. Sowing depth should be about 10mm; seed sown deeper than this may fail to establish. Seed sown into a loose seedbed may lodge later.

Timing of planting

Sow switchgrass when the surface soil is warm. Best results will come from soil temperatures above 10C and when there is some moisture in the seedbed but not when it is too wet. Avoid dry seedbeds, because it can result in poor germination and establishment. In northern Europe sowing would normally take place in late April or May. A good guide to the conditions required for planting switchgrass is that they about the same as that for planting *maize (Zea mays*). When switchgrass is sown too early the seedlings will not be able to compete with the weeds due to the relatively high temperature requirement for the grass.

Seed rate

Seed rate is based on the number of live seeds and germination rate (pure live seeds). Germination rate can vary widely with switchgrass depending on the age of the seed. Freshly harvested seed has a high dormancy and often seed is stored for a year before it is used. Germination can be improved by stratifying seeds. Before seed is purchased it will have been germination tested and the percentage of pure live seed calculated, from the information the seed rate is calculated. Still, storage may change seed dormancy and it is recommended that a simple germination test be performed to check seed germination rate. Very little information is available on optimum seeding rates in Europe. The best estimate is that a seeding rate of 400 PLS per m^2 should be adequate in NW Europe and 200 PLS per m^2 southern Europe. This means that the seed rate will be between 10 kg and 20 kg /ha.

Drilling equipment

Switchgrass seeds are small, and have a hard polished skin. There are about 500-1000 seeds/g depending on the variety. If a cereal drill is used, it may require a small seeds roll to be fitted. The seed drill must be capable of sowing the seed evenly along the row. Row width should be around 15cm.

Weed control

Growth is slow in the first year and seedlings compete badly with weeds. Keep in mind that weeds only have to be managed so that enough switchgrass seedlings survive the first winter and re-grow in spring. When this can be achieved generally no further weed control is necessary in following years as switchgrass will out-compete weeds when temperatures increase in spring.

Good and timely seedbed preparation, possibly preceded by a false seedbed, is necessary.

To increase the chances of adequate establishment and re-growth after the first winter, herbicides can be used. Keeping in mind that at the moment, to our knowledge, no herbicides have been specifically been registered for switchgrass. Glyphosate can be applied before seedbed preparation. Atrazine can be safely used pre or post emergence. To check broadleaf weeds ioxynil, bromoxynil, mecoprop, bentazone, and CMPP have been used on switchgrass.

Some of the herbicides can cause scorching and check growth. Use all herbicides at low dose rates and apply more if necessary. The most important mechanical weed control measure is mowing of weeds just above switchgrass height, when necessary. It is important not to cut the leaves switchgrass seedlings because this can seriously jeopardise the ability of the plant to survive the winter.

Pest and disease control

Diseases have not been a problem in switchgrass in Europe but crops still require regular inspection. No serious problems from pests have been reported. If there is a problem from rabbits, field margins should be fenced.

Yield development

Depending on the soil type optimal productivity is reached in 2-3 (on light soils) to 4-5 years (on heavy soils. Yield in the first year is low and it at northern latitudes may not be economic to harvest. In the second year yields can be 8-10 t dm/ha and increase further in the third year. Early frosts or droughty conditions may delay the development of full yield potential.

Management of the established crop

Established switchgrass can compete effectively with weeds when temperatures rise in spring. Lodging can be a problem.

Harvest

When switchgrass is grown for biomass (energy, fibre, etc) delayed harvest in winter/early spring is recommended. Harvesting the crop before senescence (in fall) will lead to lower winter survival and reduced spring re-growth and possibly leading to stand loss. The harvest is executed using normal grass baling methods and equipment. If the crop is to be stored for a longer period the moisture content should not be above 15-20%. The rate of dry-down and the moment of re-growth determine the harvest window in winter/early spring. If the crop is not lodged, the crop has had time to senesce and the stems are thin enough, adequate moisture content reduction will be reached before re-growth in spring.

Production cost

Preliminary estimates of the production cost (without land cost) of switchgrass vary between 24 Euro per tonne DW in Greece and 62 Euro per tonne DW for the Netherlands. The costs should compare favourably to *Miscanthus* since the cost and associated risk of establishment is lower.

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Switchgrass seed is available commercially though: Sharp Brothers Seed Company
Tel: +1-660-885-7551
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http://www.sharpseed.com

Update information can be obtained at:
www.switchgrass.nl

Annex: A switchgrass bibliography

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Introduction

Switchgrass occurs naturally east of the Rocky Mountains and south of 55°N latitude down into Mexico and Central America (Moser and Vogel, 1995). It is one of the main species of the North American tall grass prairies. In North America the grass is planted for forage, erosion control and wildlife cover (Moser and Vogel, 1995; Nielsen, 1944). The species can also be found on other continents where it is grown for forage production (Osman, 1979; Stritzler al., 1996). Since the late 80's the species has been studied as a biomass crop for renewable energy production in the USA and Canada. The main uses are for electricity production through gasification, co-combustion in coal plants and ethanol production for transportation fuel (Samson and Omielan, 1992; Sanderson et al., 1996; Turnhollow, 1991). Recently other uses have been added to the switchgrass potential like paper pulp (Girouard and Samson, 1998; Radiotis et al., 1996) and fibre reinforced composite materials.

Switchgrass was chosen by the US-DOE as a model lignocellulosic biomass crop for energy production because of its high productivity across a wide geographic range, suitability for marginal quality land, low water and nutrient requirements and environmental benefits (McLaughlin et al., 1996; Sanderson et al., 1996). The environmental benefits include low pesticide requirements, erosion control, good wildlife cover and potential for soil improvement (McLaughlin et al., 1997; Sanderson et al., 1996). Compared to annual row crops herbaceous energy crops like switchgrass reduce erosion by 95% and pesticide use by 90% (Hohenstein and Wright, 1994).

Plant description

Switchgrass is an erect perennial warm-season (C_4) grass that resembles a bunchgrass, it spreads slowly by seeds and rhizomes. The plant has erect stems that can be between 0.5 and 2.7 m tall and often have a reddish tint. The inflorescence is an open panicle 15 to 50 cm long the root system can be up to 3 m deep (Beaty et al., 1978; Christian and Elbersen, 1998; Moser and Vogel, 1995). A distinct characteristic is the white hairs where the leaf attaches to the stem.

The seed

Switchgrass has relatively small seed that can have high levels of dormancy especially just after harvest. Seed weight depends on variety and environmental conditions and varies between 70 and 200 mg 100^{-1} (Christian and Elbersen, 1998; Moser and Vogel, 1995). The seed is smooth and flows easily thought machinery, making seed drilling easy. High dormancy levels can be reduced by storing at room temperature for up to 4 years, though may also reduce seedling vigour (Moser and Vogel, 1995). Dormancy can also be broken by vernalisation when the seed is planted early in the field when conditions are cold and wet (Moser and Vogel, 1995; Smart and Moser, 1997). Several seed treatments have been tested to increase germination levels of switchgrass including ”wet chill” seed vernalisation, sulphuric acid treatments and seed priming (Beckman et al., 1993; Tischler et al., 1994; Parrish et al., 1997). New varieties are being developed with reduced seed dormancy (Ocumpaugh et al., 1997). Seed production typically varies between 220 and 560 Kg ha^{-1} but can reach 1000 kg ha^{-1} (Moser and Vogel, 1995). Prices for seed vary considerably from year to year due to bad harvests and fluctuating demand.

Seedling morphology

Two types of seedling morphology are generally distinguished in grasses; the “panicoid” type and the “festucoid” type (Fig 2) (Hyder et al., 1971; Tischler and Voigt, 1987). Most cool season (C_3) grasses, like tall fescue (*Festuca arundinacea* L.) and ryegrass (*Lolium perenne* L.), have festucoid seedling morphology. Warm season (C_4) grasses, like switchgrass, have panicoid seedling morphology. In festucoid seedlings the coleoptile elongates while the crown node, from which secondary roots and leaves originate, remains at seed level. In panicoid seedlings the mesocotyl (also called the subcoleoptile internode) elongates and pushes the small coleoptile to the soil surface, thus placing the crown node just under and sometimes at the soil surface (this feature makes seedlings easy to recognize in the field). Adventitious (secondary) roots develop from the crown node if moist conditions exist for several days (Newman and Moser, 1988). When the soil surface is dry no adventitious (secondary) roots will develop at the crown node, so the seedling will depend on the primary root and supply capacity through the mesocotyl for water and nutrients. Since the capacity for water and nutrient supply through the mesocotyl is small this will eventually limited seedling growth (Redman and Qi, 1992). Another detrimental effect is that the seedling is only loosely attached to the soil by the thin mesocotyl and can easily break off. Thus, establishment of panicoid seedlings can be divided into two critical phases for which sufficient moisture is required. Adventitious (secondary) roots develop from the crown node if moist conditions exist for several days (Newman and Moser, 1988). For example, the seedling of blue grama (*Bouteloua gracilis*) requires one period of moist soil conditions to germinate and emerge and a second moist period of about 3 days 2 to 8 weeks after emergence to form secondary roots at the crown node (Wilson and Briske, 1979). A seedling can be considered established when sufficiently long secondary roots have been formed so that the seedling can grow to sufficient size before the onset of winter (Hyder et al., 1971; Newman and Moser, 1988; Ries and Svejcar, 1991). Winter survival is generally considered the real test of plant establishment. Germplasm has been selected for lower crown node placement which is expected to have superior establishment characteristics (Elbersen et al., 1998; Tischler and Voigt, 1995; Tischler et al., 1996).

Ecotypes, ploidy levels and varieties

Switchgrass is highly polymorphic and largely self incompatible (Talbert et al., 1983; Taliaferro and Hopkins, 1997). The basic chromosome number of switchgrass is x = 9. The ploidy levels of switchgrass vary from diploid (2n=18) to duodecaploid (2n=108) (Hulquist et al., 1996; McMillan, 1959; Nielsen, 1944; Riley and Vogel, 1982). Some populations (varieties) like KY 1625 consist of plants with different ploidy levels. Recently Hopkins et al. (1996) determined that many varieties that were considered to be hexaploids are in fact octoploids. In Table 1. the ploidy levels of most existing switchgrass varieties is given as could be determined from the literature. Seed weight varies with environmental conditions and harvest date but is generally larger for octoploid than for tertaploid varieties.
Two ecotypes are generally defined based on morphological characteristics and habitat preferences. Lowland types are generally found in floodplains, they are taller, more coarse, have a more bunch type growth habit, and may be more rapid growing than upland types (Moser and Vogel, 1995; Porter, 1966). Upland types are found in drier upland sites, they are finer stemmed, broad based, and often semi-decumbent. Lowland ecotypes have more of a bunchgrass form with an elevated crown (Porter, 1966), which can increase cold injury problems. Wullschleger et al. (1996) found that maximum single leaf photosynthesis rates were higher for lowland than for upland varieties. After a drought period, later in the season, this difference was reversed, with lowland varieties having lower maximum single leaf photosynthesis rates than upland varieties. Lowland types are primarily tetraploid while upland types are hexaploid to octoploid but the exact relationship between ploidy level and ecotype remains unclear (Gunter et al., 1996; Hopkins et al., 1996). Porter (1966) suggested that upland and lowland types are genetically different. Artificial hybridization between lowlands and uplands have largely been unsuccessful (Taliaferro and Hopkins, 1997). For some varieties there does not seem to be agreement in the literature on the exact ecotype. In Table 1. the ecotype of several varieties is given. Hulquist et al. (1996) suggest that lowland types may be better suited as biomass fuel plants. In the southern USA lowland varieties like Alamo and Kanlow generally yield more dry matter than upland varieties (Parrish et al., 1997). Unfortunately it seems that northern ecotypes are mostly of the upland type. New lowland and upland varieties are being developed specifically for biomass production for southern and northern regions (Taliaferro and Hopkins, 1997).
Beaty et al. (1978) made a distinction between bunch and sod forming switchgrass types; it appears that most switchgrass varieties are of the bunchgrass type.

According to Moser and Vogel (1995) the main factors determining area of adaptation of a variety are response to photoperiod, precipitation and humidity. Decreasing daylength will induce flowering in early

summer. When different varieties are grown in the same site northern ecotypes will remain shorter, flower earlier and mature earlier than southern ecotypes. Also, production of biomass will be considerably less compared to southern types. Samson et al. (1997) compared DM yield and days to maturity. The highest yielding variety, Cave-in-Rock (>12 tons DM) matured in 135 days while the lowest yielding variety, Dacotah (<6 tons DM) matured in less than 100 days. Cave-in-Rock originates at 38? 30´ and Dacotah at 46? 30´ northern latitude. Van Esbroeck et al. (1997) found that cultivars differing in length of vegetative growth produced approximately the same number of leaves before panicle emergence. The main characteristic associated with a long period of biomass accumulation was a slow rate of leaf appearance.
Southern ecotypes moved north, will often fail to mature (and produce seed) before the end of the growing season. The failure to mature can prevent winter hardening which can lead to poor winter survival (Moser and Vogel, 1995). With generally mild winters this should be less of a problem in Western Europe. Still, in the establishment year, this may cause problems if young plants fail to winter harden properly. The quality of late maturing varieties can also be reduced because biomass will not be dry at harvest (D. Christian, pers. comm.) and nutrient content of harvested biomass may be high because nutrients have not been translocated to below ground parts (Sanderson and Wolf, 1995). This will reduce the potential for regrowth in the spring and will increase the ash content of the above ground parts, which is an undesirable feature for energy conversion, paper pulping and other fibre uses. It has been observed that southern cultivars moved too far north will initially produce good harvests which can not be sustained over time as the stand thins out.

Management

It often takes several years of careful management to establish a good stand of switchgrass which will last for more than 20 years under good conditions (Myers and Dickerson, 1984). The yield of a stand can take a few years to reach maximum potential (Christian and Elbersen, 1998). The delay in maximum production is most frequently experienced on cool wet clay soils in northern regions and in northern regions where sufficient soil moisture for seedling development is a problem (Samson pers. comm.).
Seedling establishment is the most critical stage in the development of the crop. Most varieties are established by seed. A notable exception are the cultivars Miami, Stuart and Wabasso which originate in Florida, they are generally propagated vegetatively.
The most important factors in establishment of switchgrass are seed placement, seed dormancy, water availability, temperature, weed competition and time of planting. The use of herbicides is often required to ensure good establishment. Herbicide recommendations may differ between northern and southern climates and between lowland and upland varieties.
It is recommended to do a seed test and if necessary to use seed dormancy breaking methods. The official seed testing method includes a period of cold stratification. Since this is generally not what the seed will be exposed to if planted in the field a simple seed test is recommended to realistically estimate field germination before seeding (Moser and Vogel, 1995; Wolf and Fiske, 1995). Wolf and Fiske (1995) recommend a ”wet chill” vernalisation to break dormancy if seed germination is lower than 40%. Seeding (drilling) is generally done on a pure live seed (PLS) basis (Moser and Vogel, 1995). PLS is calculated by multiplying the purity (the ratio of actual seed to total weight) by the germination:
If the purity is 90 % and germination is 70 %;
PLS = 0.90 (purity) x 0.70 (germination) = 0.63 or 63%.
So for 1 kg PLS 1.59 kg bulk seed is required.

Though most seeding rate recommendations are based on weight (kg ha^{-1}) the number of germinants per m^2 is probably a better measure. Recommended seeding rates range between 2.4 and 10 kg PLS ha^{-1} (Bransby et al., 1997; Moser and Vogel, 1995; Ocumpaugh et al., 1997; Wolf and Fiscke, 1995) which translates to 200 to 800 PLS m^{-2}. Small seeded varieties would require a lower seeding rate (kg ha^{-1}) than heavier seeded varieties. The desired number of seedlings (plants) per m^2 in the first year that is required to form a good stand will vary with environmental conditions. Though 10 to 20 seedlings (plants) per m^2 can be enough to establish a adequate stand most reported seedling rates are much higher; between 80 and 300 seedlings per m^2 (Christian and Elbersen, 1998; Peters et al., 1989; Vassey et al., 1985; Vogel, 1987).

Time of seeding

Time of seeding is an important factor in establishment success of switchgrass. Both early (Moser and Vogel, 1995; Smart and Moser, 1997; Vassey et al., 1985) and late (Parrish et al., 1997; Wolf and Fiske, 1995) seeding have been advocated. Early seeding has the benefit that cold and wet conditions break seed dormancy (Moser and Vogel, 1995). The chance of sufficient rain events is increased which will ensure that soil moisture is available for seed germination and emergence, and for secondary root development (Smart and Moser, 1997). Also, the seedlings will have sufficient time to develop before the autumn, increasing winter survival. The main problem of early seeding is that soil temperatures are low which causes slow germination and seedling development. According to Madakadze (1997) the base temperature for germination is variety dependent and ranges from 5.5 to 10.9? C. Hsu et al (1985) calculated a minimum germination temperature of 10.3? C for Blackwell and Cave-in-Rock switchgrass. Kiniry et al. (1996) assumed a base temperature for Alamo switchgrass growth of 12 °C. Thus, switchgrass growth will be relatively slow in spring compared to most problem weeds; increasing relative competitiveness of these weeds. Late seeding will be preferred to reduce weed competition but it may increase drought problems, reduce emergence percentage and can increase the chance of winter-kill if the growing season is short.
In southern Texas switchgrass is sometimes planted in late summer or fall. The seedling will develop sufficiently to survive the mild winter; still, winterkilling is not uncommon (Ocumpaugh et al., 1997). In some areas of the northern Great Plains “dormant plantings” are made in late fall so the seed overwinters, is vernalized and germinates in spring as the weather warms up but spring plantings are generally preferred (Moser and Vogel, 1995).

Seedbed preparation and planting

Seedbed preparation should be such that weeds are avoided and accurate seed placement is possible. Measures include planting a smother crop such as a small grain (Wolf and Fiske, 1995; Ocumpaugh et al., 1997). Having corn as a previous crop can increase weed problems since many problem weeds in corn are also a problem in switchgrass. Planting can be done no till or in a smooth clean and firm seedbed. A precision seed drill should be used with a planting depth of about 1cm (Christian and Elbersen, 1998; Moser and Vogel, 1995). A firm seedbed will also facilitate proper seed placement. It is recommended that before and after drilling the soil is well compacted to assure good seed soil contact.

Weed control

Switchgrass is often established without herbicides in the USA. However, weed competition is a mayor reason for stand failure. Most seedings will require some form of weed control measure. Frequently weed pressure is so heavy that it is hard to find switchgrass seedlings in the field. Because of this many switchgrass plantings are given up unnecessarily, when measures can still be taken to ensure stand establishment. It is important to be able to recognise switchgrass seedlings in the field. Application of herbicides and mowing will generally be sufficient to allow switchgrass to eventually out compete weeds as temperatures increase and a good stand will develop. A list with herbicides that have been used in switchgrass and appropriate references is given in Table 2.

A desiccant or a contact herbicide is generally used several weeks ahead and again just before seeding (Wolf and Fiske, 1995). Glyphosate, paraquat and herbicides with hormonal action like 2,4-D, dicamba or MCPA are often used. The second application just before seeding should be at a lower rate.
Switchgrass has seedling and mature plant tolerance to atrazine (and also simazine) (Martin et al., 1982) herbicides which are frequently used at seeding (Christian and Elbersen, 1998; Moser and Vogel, 1995). Still, there are indications that atrazine and also simazine can cause injury to small seedlings, especially to lowland ecotypes (Samson, pers. comm.; Bovey and Hussey, 1991). Another problem is that the use of atrazine and simazine are not permitted or will be phased out soon in most European countries. Pre-plant incorporation of bensulide and butylate is often used in switchgrass (Bransby et al., 1997; Samson pers. comm.). In the USA imazethapyr and imazameth have been tested for use in switchgrass (Samson, pers. comm.; Vogel et al., 1997). Bensulide, butilate, imazehtpyr and imazameth are not registered in The Netherlands and probably also not in the rest of Europe. Options for pre-emergence herbicide application are limited in Europe.

For post-emergence broadleaf weed control 2,4-D is often recommended when the switchgrass seedling has at least five leaves (Moser and Vogel, 1995), or 4 fully expanded leaves (Wolf and Fiske, 1995), or 3 or more tillers (Ocumpaugh et al., 1997). Especially in the early seedling stage switchgrass can be damaged by 2,4-D and slow down establishment (Bovey and Hussey, 1991; Samson pers. comm.). Dicamba another broadleaf herbicide is also frequently used but can also damage switchgrass seedlings and slow establishment (Halifax and Scifres, 1972; Samson pers. comm.). If 2,4-D and Dicamba are applied, low rates should be used. MCPA is a mild hormone herbicide against dicots that can be applied post-emergence without much risk to grass seedlings. Bentazon, is used against dicots and is safe for C_4 grass seedlings (Samson pers. comm.). Other post emergence herbicides for broadleaf control switchgrass include sulfometuron, metsulfuron and chlorsulfuron (Bransby, 1997; Samson pers. comm.). These herbicides are not registered in The Netherlands and probably also not in the rest of Europe. In England ioxynil, bromoxynil, and mecoprop-P have been used for broadleaf weed control more than a month after seeding (Christian, pers. comm.). Bentazon, MCPA and mecoprop-P applied as late as possible are probably the safest choice for broadleaf weed control in the establishment year. Grassy weeds are harder to suppress with post-emergence herbicides. Mowing just above switchgrass height is probably the best measure against competition from grassy and also other weeds (Wolf and Fiske, 1995: Ocumpaugh et al., 1997).

In the second year applications of isoproturon, atrazine, simazine, 2,4-D, glyphosate and paraquat are used to control weeds in early spring when switchgrass has not yet emerged (Christian and Elbersen, 1998; Wolf and Friske, 1995; Ocumpaugh et al., 1997). Metolachlor, a herbicide used in corn, is also used in switchgrass (Hopkins, 1995b). In England ioxynil, bromoxynil, and mecoprop-P have been used for broadleaf weed control in the summer (Christian pers. comm.). As in the establishment year bentazon, MCPA and mecoprop-P and also 2,4-D and dicamba are probably the best choice for broadleaf weed control. Still, a well-established switchgrass stand is very competitive to all weed competition.

Row distance

Row distance is an important factor in determining switchgrass productivity. A narrow row distance will accelerate canopy closure in spring which will increase total light interception over the season and thus crop productivity. Earlier crop closure will also reduce weed competition. Problems include self-thinning, which reduces total biomass yield. Also, dense crops will have more disease and lodging problems. Several row spacing studies have been conducted in switchgrass. Ocumpaugh et al. (1997) compared row spacings of 15, 30 and 50 cm and found that in drought conditions wider spaced treatments had higher yields. Bransby et al. (1997) found that in Alabama wide spaced (80 cm) stands yielded more than narrow spaced stands (20 cm) after the first year. The yield increase was especially evident several years after establishment. Still, in the literature a row spacing of 15 to 20 cm is most common. In view of the possible weed problems and slow crop closure under low temperatures a row distance of 15 cm is probably best for the current project.

Fertilization and yield

Switchgrass will tolerate acid and infertile soil conditions that will not support cool-season grasses. Switchgrass will tolerate a soil pH of 4.9 up to 7.6 (Moser and Vogel, 1995), but will establish and grow better if pH is amended to neutrality (Jung et al., 1988). Porter reported switchgrass growing in soils with a pH of 8.9 to 9.1 (Porter et al., 1966). Taliaferro and Hopkins (1997) found that in the seedling phase cv. Kanlow and Blackwell were highly tolerant of acid soils ranging from pH 4.4 to 5.1 and concluded that breeding for increased acid soil tolerance is not warranted because of existing high tolerances.

As mentioned, fertilization (especially N) is not recommended in the first year since this will stimulate weed competition. On light soils and in southern regions a small amount of nitrogen can be given later in the season of the establishment year. After the first year fertilisation should still be delayed to later in the season when weed pressure is lower. If nitrogen fertiliser is not fully utilised by the end of the season N-carryover can increase weed competition in the following spring (Moser and Vogel, 1995). Switchgrass makes good use of organic nitrogen since highest growth rates occur when mineralization of organic N is highest (Moser and Vogel, 1995). The high rate of mineralisation and uptake by switchgrass may contribute to lodging, a problem that has been encountered in England and Canada (Christian pers. comm.; Samson pers. comm.). Biomass lodging has also been reported at high N-rates in Texas after drought (Ocumpaugh et al., 1997). On heavy soils with high N contents switchgrass will often not show a response to nitrogen for several years after establishment (Christian and Elbersen, 1998; Samson pers. comm.).

Harvest management has an important influence on fertiliser requirement of the crop. Parrish et al. (1997) harvested Cave-in-Rock switchgrass at monthly intervals from September to April. Biomass yields declined from September to November from 13.6 to 9.8 tonnes ha^{-1} and to 8.9 tonnes ha^{-1} in April. There was a 12% lower yield in the following season when the previous year’s harvest had been made in September or October. It was estimated that in the period from September to senescence 10% of the biomass is translocated to the below ground parts, which included as much as 72 kg N ha^{-1}.

On light soils in Texas, with high productivity and harvests during the growing season Ocumpaugh et al. (1997) found a N-response up to 200 kg N ha^{-1}. When switchgrass is harvested for biomass after the winter most of the nutrients will be recycled within the plant or return to the soil through sheded leaves. The amount of nutrients that is removed from the system is small. The lack of a N-response on a heavy soil over several years as reported by Christian (pers. comm.) illustrates this effect.

It has been estimated that for biomass production switchgrass only requires 50 kg N ha^{-1} (Turnhollow et al., 1991). For the American great plains N fertiliser recommendations are given for grazed switchgrass depending on precipitation, they vary between 50 and 100 kg ha^{-1} N for areas with 450 and 750 mm of precipitation per year respectively (Moser and Vogel, 1995). For established stands the best guideline for N fertiliser application is probably to fertilise at the extraction rate which is approximately 6-10 kg ton^{-1} DM for fall harvests and 4-8 kg ton^{-1} for early spring harvests (Samson, pers. comm.). Lighter soils have about 25% higher N requirements.

Most studies on phosphate fertilisation report that switchgrass does not show a response to P-fertilisation even if soil values are low (Jung et al., 1990; Jung et al., 1988; Ocumpaugh et al., 1997).

During the growing season nutrient concentration of switchgrass declines. Calcium and Mg concentrations do not change much, while K, P and total ash will decline significantly (Parrish et al., 1997; Sanderson and Wolf, 1995). Allowing switchgrass to reach maturity will minimise concentrations of inorganic elements. This increases quality of the biomass for combustion and other uses. Jung el al. (1988, 1990) found that switchgrass will tolerate soils with much lower mineral levels than C_3 grasses, making lower soil mineral recommendations possible. Parrish et al. (1997) concluded that high yields can be produced from soils with low to medium soil test nutrient levels and that fertiliser application needs to be based on management systems rather than yield.

Diseases

Diseases and insect plagues are generally not a problem in new or established stands since most cultivars are genetically diverse and have significant levels of resistance (Moser and Vogel., 1995; Samson, pers. comm.; Wolf and Fiske, 1995). Varieties adapted to dry areas like the Great Plains will often develop more foliar disease problems (rusts) when grown in humid places (Moser and Vogel, 1995). Disease pressure is most severe where overnight dew occurs. Few specific diseases of switchgrass are discussed in the literature. Spot blotch (*Helminthosporium sativum* L.) has been studied (Zeiders, 1984). Moser and Vogel (1995) mention that lowland types are generally more resistant to rusts (*Puccinia* spp.) than upland types.
In young seedlings damping off diseases and insect predation may be a problem (Wolf and Fiske, 1995). In the first year seedling establishment can be improved with the use of insecticides (McKenna et al., 1991; Parrish et al., 1997). Switchgrass is susceptible to the maize streak monogeminivirus, panicum mosaic satellivirus and Panicum mosaic sobemovirus (Brunt et al., 1996).

Mycorrhizae

Hetrick et al. (1988) showed that several warm season (C_4) prairie grasses, among them switchgrass, inoculated with the mycorrhizal fungus *Glomus etunicatum* Becker and Gerd. yielded much more compared to non-inoculated grasses. Koslowsky and Boerner (1989) found that switchgrass inoculated with vesicular-arbuscular mycorrhizae (VAM) outgrew non-VAM plants at medium and low levels of soil Aluminium. Brejda et al. (1993) showed that switchgrass is highly mycorrhizal dependent on sandy soils and concluded that establishment on eroded sites may be greatly improved by inoculation with mycorrhizae. Vogel et al. (1997) found that in greenhouse studies mycorrhizae significantly improved switchgrass growth demonstrating that switchgrass is a mycorrhizae dependent species. In field studies inoculation of switchgrass seedlings with VAM had no significant effect on growth. It was concluded that indigenous mycorrhizae are effective with switchgrass and that inoculation of fields with mycorrhizae for switchgrass biomass production will not be needed.

In how far the lack of specific mycorrhizae at European experimental sites will play a role is not known. It seems that many different mycorrhizae can inoculate switchgrass.

Soil carbon

The use of energy crops and renewable materials contribute to reductions of CO_2 emissions, which is one of the main reasons for the interest in this subject. It is therefore important to quantify the total contribution of switchgrass to the CO_2 balance. Apart from the storage of carbon in the aboveground biomass, storage of carbon in the soil can play an important role.

Parrish et al. (1997) quantified the root mass in the top 30 cm of the soil profile under switchgrass crops in the upper southeast of the USA. The root mass varied greatly (2,7 to 18,6 Mg ha^{-1}) with an average rootmass of 8,2 Mg ha^{-1}. This was generally much higher than of tall fescue (*Festuca arundinacea*) a C_3 grass. Roots were also much more abundant deeper in the soil when compared to tall fescue. Zan et al. (1997) found that corn (*Zea mays*) produced higher above ground yields (16,2 Mg ha^{-1}) compared to switchgrass (14,2 Mg ha^{-1}) but corn had much less below-ground biomass (1,6 Mg ha^{-1}) compared to switchgrass (7,2 Mg ha^{-1}). Ocumpaugh et al.(1997) found that in Texas the average soil carbon levels increased from 10 to more than 12 g kg^{-1} after 3 years of switchgrass cover. Wullschlager et al. (1997) calculated a soil organic matter turnover time of 26 to 44 years under long-term switchgrass plantings in Tennessee.

Harvest

Harvesting of switchgrass can be done with conventional grass harvesting machines (Christian and Elbersen, 1998). In Europe switchgrass should probably be harvested in the winter when stems have dried out sufficiently. The thin woody stems of switchgrass allow good dry down in the winter. This may increase the harvest window of switchgrass compared to a crop like Miscanthus, which has thicker stems which would be expected to dry down slower. At Rothamsted moisture content at harvest was down to 30%, which may allow the baled crop to be stored for a short period before use, without the need for drying (Christian and Elbersen, 1998). Lower moisture contents may be possible in some parts of Europe where the continental climate gives drier winters.

Harvest and transport management of switchgrass has a large influence on energy conversion quality of switchgrass. Contamination of switchgrass samples with dirt during harvest and storage can increase alkali and ash content considerably (McLaughlin et al., 1996). Lodging can also complicate harvest and decrease quality due to higher moisture content and soil contamination.

The high C/N ratio of switchgrass biomass may make it possible to bale switchgrass at moisture levels of up to 20%, as has been found for ryegrass straw (Nay, 1996??).

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Table 1. Switchgrass varieties and their ecotype, ploidy level and area of origin and adaptation.

Variety	Ecotype	Ploidy level	Origin » latitude	Maturity	100 seed wt., mg	Comments	References
Alamo	lowland	Tetraploid	south Texas≈27.00	very late	94	Up to 2.5 m high, course, late flowering, >630 mm rain,	Alderson and Sharp, 1993; Anonymous. 1979; Gunter et al., 1996; Hopkins et al., 1996.
Blackwell	upland	Octoploid	northern Oklahoma ≈36.70	mid/ late	142	disease resistant, heavy stems, medium height, 380-760 mm, also in lowland, sandy areas	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996, Hopkins et al., 1995a.
Caddo	upland	Octoploid	central Oklahoma ≈34.80	late	159	Plants tall, robust, high seed production, forage yield under irrigation outstanding. Excellent seedling vigour, resistant to leaf rust.	Alderson and Sharp, 1993; Gunter et al., 1996; Hein, 1958; Hopkins et al., 1996
Carthage=NJ-50	?	?	North Carolina ≈36.00	late	148		Alderson and Sharp, 1993; Stout et al., 1988; Jung et al., 1990.
Cave-in-rock	upland/ lowland	Octoploid	southern Illinois ≈38.30	min/late	166	Medium to coarse. Resistant to zonate leafspot and rust, good in humid conditions. 1.5 m tall, well drained soils, moderate seedling vigour, coarser than Pathfinder and Blackwell	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996;George and Reigh, 1987.
Dacotah	upland	Tetraploid?	North Dakota ≈46.30	very early	148	Adequate forage and higher latitude of adaptation, short, early maturing.	Alderson and Sharp, 1993; Barker et al., 1990; Gunter et al., 1996.
Falcon	?	?			165		
Forestburg	upland	Tetraploid?	South Dakota ≈44.20	early	146	Forage yield high. very winter hardy, persistent, early,	Alderson and Sharp, 1993; Barker et al., 1988; Gunter et al. 1996;
Grenville	?	?			188	collected at 1800m, low rain, fine stemmed	Alderson and Sharp, 1993.
Kanlow	lowland	Tetraploid	central Oklahoma ≈34.80	very late	85	Tall, coarse, poorly drained soils, wide adaptation, not drought tolerant, slow establishment	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996; Hopkins et al., 1995a.
KY 1625	mixed	Octoploid?	West Virginia ≈39.00	mid	143	Fine stems, leafy, late maturity, poor seed quality.	Alderson and Sharp, 1993; Henry and Taylor, 1989; Hopkins et al.,

							1996.
Miami	?	Tetraploid	southern Florida ≈27.00	very late		Increased vegetatively	Gunter et al., 1996; Hopkins et al., 1996.
Nebraska 28	upland	?	northern Nebraska ≈42.60	early / mid	162	Well adapted to diverse soils. Susceptible to rust in areas with longer season than Nebraska. Used for forage and stabilization. semi decumbent, fine stems,	Alderson and Sharp, 1993. Hopkins et al., 1995a.
NL 93-1	lowland	?	36-40, 223 days to heading		121	Developed at OSU by Taliaferro and Hopkins	Taliaferro and Hopkins, 1997
NL 93-2	lowland	?	36-40, 223 days to heading		89	Developed at OSU by Taliaferro and Hopkins	Taliaferro and Hopkins, 1997
NU 94-2	upland	?	36-40, 210 days to heading		173	Developed at OSU by Taliaferro and Hopkins	Taliaferro and Hopkins, 1997
Pangburn	?	Tetraploid	Arkansas		96		Hopkins et al., 1996
Pathfinder	upland	Octoploid	Nebraska / Kansas ≈39.90	mid / late	187	good establishment, vigorous, winter hardy, leafy, rust resistant	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996; Newel, 1968.
PMT-279	lowland	Tetraploid	southern Texas ≈29.00				Gunter et al., 1996; Hopkins et al., 1996
REAP 921	upland	Tetraploid	south Nebraska	early / mid	90	resistant to lodging in Canada, small seeded, somewhat slow to establish	Samson pers. comm.
Shawnee	upland	Octoploid	South Illinois ≈38.30	mid / late		Cave-in-Rock is base, high IVDMD	Vogel et al., 1996;
Shelter=NY4006	mixed?	Octoploid?	West Virginia ≈41.70	mid	179	Upright, stiff, thicker stems, fewer leaves, lower seedling vigour, 7-10 days earlier then Blackwell,	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996.
Stuart	?	Tetraploid	Florida ≈28.50	late		Increased vegetatively	Hopkins et al., 1996
SL 93-2	lowland	Tetraploid?	26-30, 231 days to		87	Developed at OSU by Taliaferro and Hopkins	Taliaferro and Hopkins, 1997

			heading			derived from Alamo and related germplasms	
SL 93-3	lowland	Tetraploid?	26-30, 234 days to heading		100	Developed at OSU by Taliaferro and Hopkins derived from Alamo and related germplasms	Taliaferro and Hopkins, 1997
SL 94-1	lowland	Tetraploid?	26-30, 233 days to heading		91	Developed at OSU by Taliaferro and Hopkins derived from Alamo and related germplasms	Taliaferro and Hopkins, 1997
SU 94-1	upland		32-34 south central Oklahoma		183	Developed at OSU by Taliaferro and Hopkins	Taliaferro and Hopkins, 1997
Summer	upland	Tetraploid	south Nebraska ≈ 40.80	late/ mid	113.5	mostly rust resistant, tall for north, upright, coarse leaves, high yield of forage and seed.	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996.
Sunburst	upland	?	South Dakota ≈ 43.80	mid	198	Winter hardy, leafy, and heavy-seeded, good seedling vigour. Anthesis early August in eastern SD.	Gunter et al., 1996; Hopkins et al., 1995a.
Trailblazer	upland	Octoploid	Nebraska ≈ 40.00	mid	185	High IVDMD, compare to Pathfinder	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996; Vogel et al., 1991.
Wabasso	lowland	Tetraploid	southern Florida ≈27.00	very late		Increased vegetatively	Hopkins et al., 1996.
9005439	upland		wheatland Wyoming		183	Northern, tall, leafy, dark green, disease resistant,	pers comm. Connie Reynolds NRCS-PMC
9005438	lowland		Wyoming	later	177	Southern, light green, leafy, tall, high production	pers comm. Connie Reynolds

Table 2. Herbicides used in switchgrass.

Official name*	Other names	Action	When?	Available?	Problems	Reference
Atrazine	In Laddock	inhibits photo system A	pre-emergence/ post emergence	Not in Germany or Italy	Can hurt seedlings, especially lowland types. Use when seedlings have 5 leaves. Use low doses; 800 g/ha. Generally reduces seedling numbers and DW if used preplant. in Alamo less problems if foliar applied	Samson pers. comm.; Vassey et al., 1985; Moser and Vogel, 1995; Vogel, 1987; Martin et al., 1982; Sledge and Walker, 1993
Bensulide			pre-plant incorporated	Not in NL?	Generally reduces seedling numbers and DW	Bransby et al., 1997; Samson pers. comm.; Bovey and Hussey, 1991; Sledge and Walker, 1993
Bentazon	Basagran	inhibits photo system B	pre-emergence	OK in NL	Good against dicots. Used in Canada, safe for C4 grasses	Samson pers. comm. Rotteveel pers. comm.
Bromoxynil		inhibits photo system B		OK in NL	Against dicots in establishment year and in mature stand. can injure seedlings in warm weather.	Rotteveel pers. comm. Christian pers. comm.
Butylate				Not in NL		Samson, pers. comm.
Chlorsulfuron	Glean		pre-emergence/ post-emergence	Not in NL?	pre-emergence tolerated 0.006 lb/A post-emergence excessive injury	Samson pers. comm. Chenault and Wiese, 1988 Bovey and Hussey, 1991
Dicamba	Banvel	hormone			Too harsh! It should only be used in cloudy weather larger seedlings	Samson pers. comm. Rotteveel pers. comm. Ocumpaugh, 1997
Fluroxypyr?	Starane	hormone		Not in USA?	Can injure seedlings? Against broadleaf weeds - against monocots-	Rotteveel pers. comm. Christian pers. comm.
Glyphosate	Roundup	inhibits aminoacid synthesis B			More effective (aggressive) than paraquat.	Rotteveel pers. comm. Wolf and Fiske, 1995
Imazameth	Plateau	inhibits acetohydroxyacid synthase	pre-emergence	New in USA. Not available in Europe?	New in USA, switchgrass is tolerant	Samson pers. comm. Vogel et al., 1996
Imazethapyr	Pursuit		pre-emergence	Not in NL?	Generally reduces seedling numbers and DW(pre-emerg.) Postemerge it is better tolerated	Wilson, 1995; Samson pers. comm Sledge and Walker, 1993
Ioxynil		inhibits photo system B			against dicots in July of establishment year and in mature stands	Christian, pers. comm.
Isoproturon?		inhibits photo system B		Not in USA?		Christian, pers. comm.

MCPA		Hormone			Against dicots not too strong, safe	Rottevell pers. comm.
Mecoprop-P		Hormone			against dicots	Christan pers. comm.
Metsulfuron-methyl	Ally	inhibits ALS	post-emergence/ pre-emergence		post-emergence good tolerance (0.02 kg/ha) or injury (0.004 lb/A). pre-emergence tolerance (0.006 lb/A)	Chenault and Wiese, 1988; Bransby et al., 1997; Samson pers. comm; Sledge and Walker, 1993
MSMA			post-emergence	Not in NL	Good tolerance, 2.24 kg/ha, with 2,4-D can damage switchgrass	Sledge and Walker, 1993 Bransby et al., 1997 Chenault and Wiese, 1988
Paraquat	Gramoxone	Inhibits photo system C	before planting or regrowth		Before emergence in mature stand	Christan pers. comm.
Simazine		inhibits photo system A	pre-emergence		Can damage switchgrass seedlings? will be phased out?	Christian and Elbersen, 1998
2,4-D		hormone	post-emergence		Generally hurt seedlings! or can hurt seedlings, use as late as possible	Samson pers. comm.; Bovey and Hussey, 1991; Sledge and Walker, 1993; Ocumpaugh et al., 1997; Moser and Vogel, 1995

* Anon. 1997. Common & chemical names of herbicides. J. Prod.. Agric., 10(4):iv-vi.